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13. ABSTRACT (Maximum 200 words)

The report describes research performed at Stanford University to investigate ram accelerator phenomena using expansion tube and shock tube facilities. The program included three coordinated elements: imaging and modeling of oblique detonations and shock-induced combustion in high-speed wedge and blunt body flows; experimental investigations of fuel jets in supersonic combustion; and measurements and modeling of ignition kinetics propulsion fuel mixtures. The objectives of this research were: to establish modern experimental capabilities for the study of high-pressure reactive gasdynamics; to measure critical chemical reaction rate parameters relevant to the modeling of ram accelerators; and to provide species flow field distribution information needed for the evaluation of CFD codes used in the study of ram accelerator phenomena and shock-induced combustion.

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1) STATEMENT OF THE PROBLEM STUDIED

The ram accelerator is a novel propulsion strategy pioneered in the late 1980s by researchers at the University of Washington (UW). In a ram accelerator, a projectile is fired at supersonic velocity into a tube filled with a premixed gaseous propellant mixture. A structure of shock waves forms around the projectile which increases the pressure and temperature sufficiently to ignite the gas mixture. The energy release from combustion provides thrust which continuously accelerates the projectile down the length of the tube. The UW research group has successfully built and tested a 37-mm ram accelerator in their laboratory. In recent years, the US Army has also built a 120-mm ram accelerator at the ARL at Aberdeen Proving Ground.

A major problem in ram accelerator research is the lack of detailed understanding of the actual flow physics and chemistry around the projectile. Work at Stanford has been aimed at developing an improved understanding of high-speed exothermic gas flows through the application of modern experimental methods and finite-rate-chemistry flowfield modeling. Thus far, the emphasis has been on providing fundamental data of flowfield structure and combustion ignition times. The data are particularly useful for improving the accuracy of the computational codes which support ram accelerator development.

The objectives of this research are: 1) to establish modern experimental capabilities for the study of high-pressure reactive gasdynamics; 2) to measure critical chemical reaction rate parameters relevant to the modeling of ram accelerators; and 3) to provide species flow field distribution information needed for the evaluation of CFD codes used in the study of ram accelerator phenomena and shock-induced combustion. The program has three coordinated elements: imaging and modeling of oblique detonations and shock-induced combustion in high-speed wedge and blunt body flows; experimental investigations of fuel jets in supersonic combustion; and measurements and modeling of ignition kinetics in defense-related fuel mixtures.

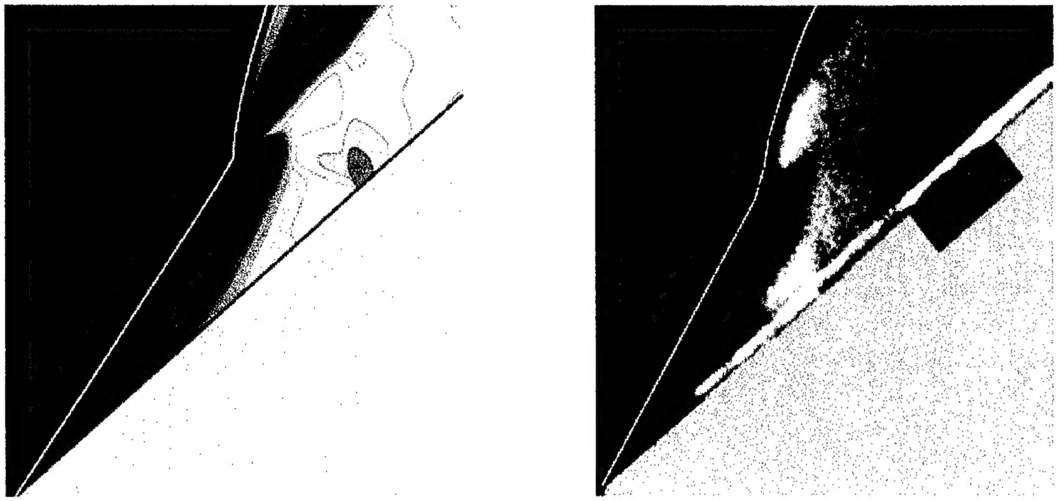
2) SUMMARY OF THE MOST IMPORTANT RESULTS

Imaging and Modeling of Hypervelocity Exothermic Flows

This study was aimed at improving understanding of pre-mixed combustion around blunt bodies and wedges at hypersonic velocities. The research has both experimental and computational elements. A dedicated expansion tube was designed, constructed and characterized for this study during 1994-95. An expansion tube is essentially a high-velocity, short-duration wind tunnel similar to a conventional shock tube. A test model is mounted at the exit of the tube. The Stanford expansion tube has successfully accelerated hydrogen-, methane- and ethylene-based fuels to velocities ranging from 1700-2200 m/s (Mach 4-7). PLIF and Schlieren imaging systems are installed in the facility. Additionally, in an effort to develop an in-house numerical modeling capability for comparison with the experimental results, two inviscid flow, finite-rate chemistry CFD codes have been developed in this program. One code, used primarily for studying the blunt body flows, was developed and tested by Dr. Toshimitsu of Kyushu University during his visit to our laboratory in 1996-97. A second inviscid flow, finite-rate CFD code explicitly designed for wedge and conical flows was also developed in the laboratory in 1998-99.

One element of this research involved the study of shock-induced combustion around blunt bodies. A number of experiments were performed in the expansion tube facility studying the impact of freestream pressure and velocity, mixture sensitivity, and body geometry on the resultant flowfield. . Both steady and unsteady combustion flows have been observed, with research emphasis on the latter case due to relevance to subdetonative ram-accelerator propulsion. A simultaneous OH PLIF and schlieren imaging technique, developed in our laboratory, was applied to visualize both the shock and reaction fronts in the flow. In addition, a pressure transducer installed in the forebody of the model provided the first direct measurements of pressure oscillations in the unsteady flows. These experiments form a database of qualitative and quantitative results which may be used to validate CFD codes studying hypersonic reactive flows. Analysis of the results shows that there are two primary unsteady modes: a small-disturbance, high-frequency regime and a large-disturbance, lower-frequency regime. The data indicate that the period of oscillation of large disturbances is a combination of a characteristic ignition timescale and a characteristic acoustic timescale. Additionally, a theory was developed predicting the transition to sustained detonation when a projectile is travelling at less than the C-J detonation velocity. The theory agrees well with ballistic range experiments performed at the University of Washington.

A second study has explored shock-induced combustion and oblique detonation wave formation in high-speed wedge flows. Oblique detonations, which occur in the limit of fast ignition behind an oblique shock, are a phenomenon of significant importance to superdetonative ram-accelerator propulsion. Experimental work primarily employed a 40° (half-angle) wedge body, while varying the gas mixture composition and pressure to alter the ignition delay and energy release. The results confirm the detachment predictions of shock polar theory, and constitute a database for validating CFD codes. Good agreement has been found between the



(a) (b)

Figure 1: Comparison of experimental and numerical results for supersonic exothermic wedge flow. (a) Experimental OH PLIF image; pressure transducer location shown in blue; shock position (in white) determined from complementary schlieren image. (b) OH contour plot from numerical calculation of flow; shock position shown in white. Mixture: $2H_2 + O_2 + 12N_2$, $V_\infty = 2130$ m/s, $T_\infty = 282$ K, $P_\infty = 0.12$ atm. Total wedge forebody length shown is 30.5 mm.

experimental results and the wedge- and conical-flow CFD code developed in our laboratory (Figure 1). Additionally, in 1999-2000, this code was used to study oblique detonation wave formation in three different regimes of wedge flows. These studies confirmed that oblique detonations can be stabilized on very shallow wedge angles. The simulations also point to the critical role of the energy-release rate, strongly dependent on the pressure, in determining how oblique shock-induced combustion transitions to an oblique detonation flow. An additional set of simulations have confirmed similar behavior in conical flows.

Transverse Fuel Jet Injection into Supersonic Crossflows

The expansion tube facility has also been used to study transverse fuel jet injection into supersonic crossflow, with a view toward improving understanding of scramjet mixing and flameholding issues. In addition to OH PLIF imaging, this study made use of an ultra-fast, intensified framing camera which enabled acquisition of eight consecutive schlieren images in each experiment. This multi-frame imaging capability resulted in a number of important observations. When the images were assembled as a movie, the pulsating nature of the upstream separation region and of the jet causing the bow shock to fluctuate became apparent, though this unsteady behavior was not anticipated. A cross-correlation FFT technique allowed the eddy velocity and formation frequency to be determined from the images. The results showed that the coherent structures tend to travel with velocities that are closer to the free-stream velocity in the far-field ($x/d > 10$). Both hydrogen and ethylene fuel jets have been studied, with ethylene jets resulting in a much more turbulent flowfield. Additionally, a systematic study of jet penetration pointed to the importance of jet to crossflow velocity ratio as a critical factor governing penetration in these conditions.

The OH PLIF imaging results show clear differences in the flameholding capability of the jet at different freestream conditions. OH fluorescence appears first in the recirculation region upstream of the jet and extends along the outer edge of the jet plume (Figure 2) demarcating the boundary between the fuel and air. Higher-enthalpy test conditions (Flight Mach 10 and 13) show considerable reaction in the upstream recirculation region, in contrast to negligible reaction there in the Mach 8 condition.

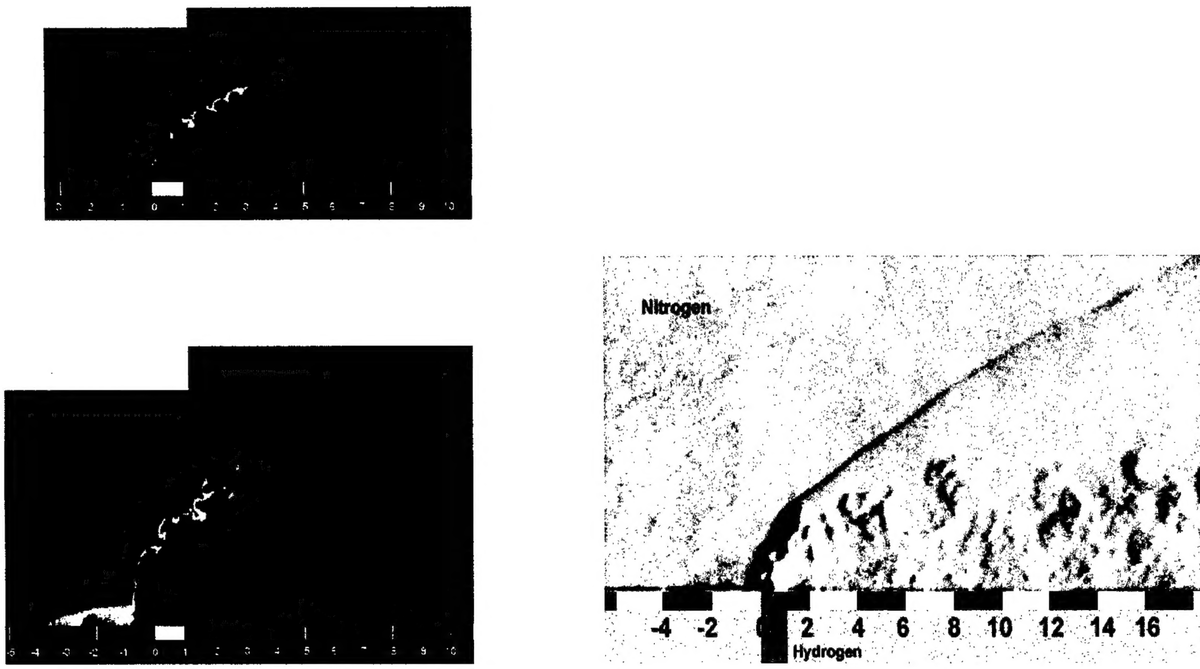


Figure 2: Right panel - instantaneous schlieren image of underexpanded hydrogen injection into supersonic cross-flow (non-reacting, nitrogen) obtained by high-speed-framing camera (exposure time of 200ns), imaging 30x50 mm^2 of flow field. Left panel - two instantaneous OH-PLIF results for Mach 10 (upper) and Mach 13 (lower) conditions. Each image is obtained by combination of 2 different instantaneous images: near the exit of the jet (-5<x/d<1) and downstream of the jet (1<x/d<10).

Measurements and Modeling of Ignition Kinetics

Ignition chemistry is important in the design of the ram accelerator to prevent premature combustion near the projectile forebody, and ignition delay time measurements provide the necessary data to extend detailed kinetics models into the appropriate operating region of interest. Such fundamental data are relevant not only to the ram accelerator, but also to the general development of finite-rate-chemistry models for detonation and ballistics studies as well.

Ignition kinetics have been studied on three fronts: development of improved ignition time measurement techniques, experimental determination of ignition times, and chemical kinetic modeling and correlation. Ignition time measurements were performed in a high-pressure shock tube capable of attaining pressures as high as 800 atm behind the reflected shock wave.

We have made three primary improvements in our methods of measuring ignition times. We now accurately measure the *in situ* fuel concentration using 3.39 μm laser absorption which avoids fuel desorption and adsorption problems which occur with condensable mixture components. This method is applicable to single component fuel mixtures, and has successfully applied to the measurement of n-heptane, n-decane and JP-10. We measure the ignition time at both the shock tube endwall location and at a sidewall location which allows us to correct the ignition times for combustion wave effects. Sidewall measurements also permit accurate ignition time determinations at low fuel concentrations, where end wall measurements have decreased precision. We use CH emission as the ignition time marker which permits a more unequivocal determination of the ignition time than that derived from the pressure rise.

Ignition delay times for a number of methane-based mixtures of importance to the ARL ram accelerator program were measured; the combination of test conditions and mixtures has provided a range of empirical correlations that completely characterize the expected range of ARL methane-based ram accelerator mixtures. We have obtained ignition delay times for a range of CH_4/O_2 mixture concentrations at realistic pre-ignition temperatures (1040 - 1600 K) and pressures (40 - 260 atm). Prior to these studies, no data existed for the extreme, high-pressure conditions of the ram accelerator, i.e., fuel-rich mixtures (ϕ up to 6.0), low diluent-gas levels (< 70%), and intermediate ignition temperatures (< 1400 K).

A 279-reaction kinetics mechanism was developed that can predict the ram accelerator ignition delay times over a broad range of mixtures and conditions. This expanded model, based on the recent Gas Research Institute methane oxidation mechanism (GRI-Mech 1.2), is able to reproduce the accelerated ignition trends seen in the data at higher pressures and lower temperatures. Reduced kinetics mechanisms for CH_4/O_2 (22 species, 34 reactions) and H_2/O_2 (9 species, 18 reactions) that faithfully reproduce the experimental ignition data have also been developed for use in ARL CFD codes. Correlations for these ignition times have also been developed.

Experimental measurement and kinetic modeling has been extended to a number of fuels related to air-breathing combustion. See Figure 3. For these larger fuel molecules ignition times, kinetic modeling and correlations based on these experiments and modeling, have been investigated. In particular for n-heptane/O_2/Ar mixtures, parametric studies of the ignition time have found well-behaved power-law dependences for ignition time as a function of pressure, fuel or oxygen mole fraction or partial pressure, and stoichiometry. These ignition times have been compared to other alkanes and JP-10. For n-heptane ignition we have also developed correlations based on the kinetic models of three groups: Dryer et al. at Princeton, Westbrook et al. at Livermore, and Lindstedt and Maurice at Imperial College.

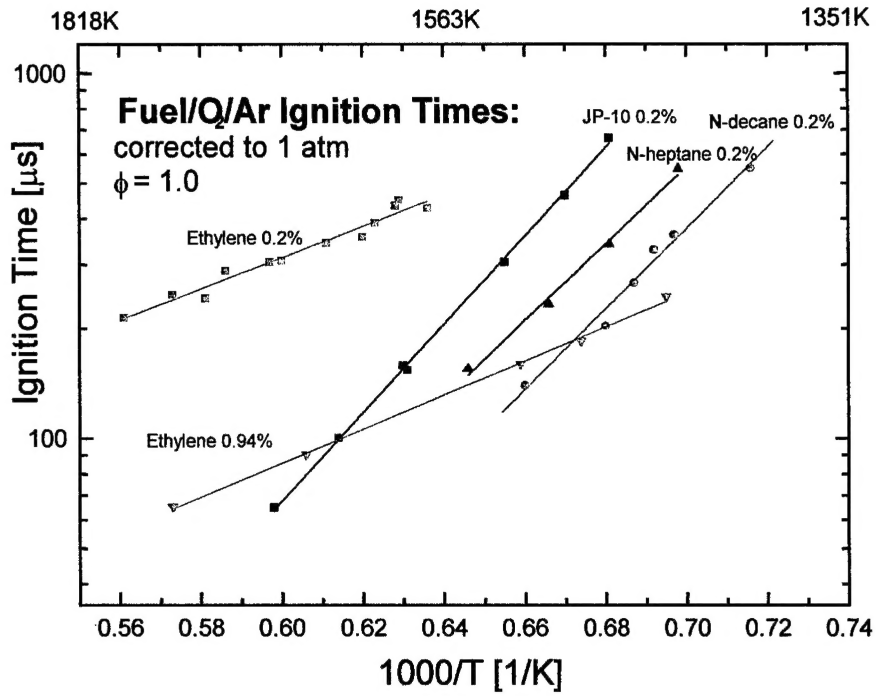


Figure 3: Representative shock tube ignition time data for several fuels.

3) LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS

2000

Ben-Yakar, A. and Hanson, R.K., "Cavity Flame-Holders for Ignition and Flame Stabilization in Scramjets: An Overview," Accepted for publication in J. of Propulsion and Power.

Ben-Yakar, A. and Hanson, R.K., "Characterization of Expansion Tube Flows for Hypervelocity Combustion Studies in the Flight Mach 8-13 Range," Submitted to J. of Propulsion and Power.

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D. C. Horning, D. F. Davidson and R. K. Hanson, "Ignition Time Correlations for n-Heptane/O_2/Ar Mixtures: A Parametric Study of Experimental Data and Kinetic Modeling," In preparation.

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4) LIST OF ALL PARTIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT

Principal Investigator:	Prof. R. K. Hanson
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6) BIBLIOGRAPHY

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7) APPENDIXES

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